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Smart Grid and Dynamic Power Management

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1. Introduction

Historically, energy has been relatively inexpensive. Efforts to manage the efficient use of electrical energy have been of secondary importance and often limited to initial architectural and design considerations. Inexpensive and widely-available energy has led to unprecedented economic growth but the costs and risks are increasing: the costs of fossil fuels, the costs to the environment, and the risks to foreign supplies.

With the passage of the Energy Independence and Security Act of 2007, the United States embarked on a path to modernize the electrical grid as described in Title XIII – Smart Grid. (US Title XIII, 2007) This modernization is transforming how energy is generated, transmitted, distributed and consumed in residential, commercial and industrial facilities but it is not changing the basic electrical constraints of the system.

Electrical supply and demand must remain in balance at all times. This balance has traditionally been attained through dispatching generation and day-ahead scheduling along with sufficient capacity reserves. Temporal load change typically follows a macro pattern based on diurnal or daily variation. Power usage increases during the day and decreases at night. It is this cycle, or load curve, which drives modern grid operations. Sufficient reserve capacity is required to meet any demand peaks. Generation failures and circuit trips also require that reserves be brought on-line. When, for any reason, supply does not equal demand, the grid can collapse resulting in a blackout.

2. What is Smart Grid

The U.S. Energy Independence and Security Act of 2007, Title XIII and the NIST (National Institute of Standards and Technology) Smart Grid Framework (SG Roadmap, 2010) describe the goals and objectives of Smart Grid. EISA Title XIII defines the following characteristics of Smart Grid:

1. “Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
2. Dynamic optimization of grid operations and resources, with full cyber-security.
3. Deployment and integration of distributed resources and generation, including renewable resources.
4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.

5. Deployment of 'smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
6. Integration of 'smart' appliances and consumer devices.
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
8. Provision to consumers of timely information and control options.
9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services."

FERC (Federal Electricity Regulatory Commission) outlined the top eight (8) U.S. National Smart Grid priorities as:

"Wide-area situational awareness: Monitoring and display of power-system components and performance across interconnections and over large geographic areas in near real time.

Demand response and consumer energy efficiency: Mechanisms and incentives for utilities, business, industrial, and residential customers to cut energy use during times of peak demand or when power reliability is at risk.

Energy storage: Means of storing energy, directly or indirectly.

Electric transportation: Refers, primarily, to enabling large-scale integration of plug-in electric vehicles (PEVs).

Cyber security: Encompasses measures to ensure the confidentiality, integrity and availability of the electronic information communication systems and the control systems necessary for the management, operation, and protection of the Smart Grid's energy, information technology, and telecommunications infrastructures.

Network communications: The Smart Grid domains and subdomains will use a variety of public and private communication networks, both wired and wireless.

Advanced metering infrastructure (AMI): Currently, utilities are focusing on developing AMI to implement residential demand response and to serve as the chief mechanism for implementing dynamic pricing.

Distribution grid management: Focuses on maximizing performance of feeders, transformers, and other components of networked distribution systems and integrating with transmission systems and customer operations."

The U.S. NIST and the Smart Grid Interoperability Panel (SGIP) created the Smart Grid Conceptual Model (SGIP CM, 2010) which describes the seven (7) primary domains that comprise Smart Grid: Bulk Generation, Transmission, Distribution, Customer, Markets, Operations and Service Provider. (See Figure 1)

"The Smart Grid Conceptual Model is a set of views (diagrams) and descriptions that are the basis for discussing the characteristics, uses, behavior, interfaces, requirements and standards of the Smart Grid." (SGIP CM, 2010)

The two domains with the greatest direct impact on the electrical supply chain are the customer (See Figure 2) and bulk generation (See Figure 3) domains as they form the core drivers for change in the electrical system.

The other domains will, in general, need to adapt to the changes in these two domains but all domains are interconnected and therefore affect each other. Changes occurring in the wholesale and retail markets will directly impact other domains. New services and service

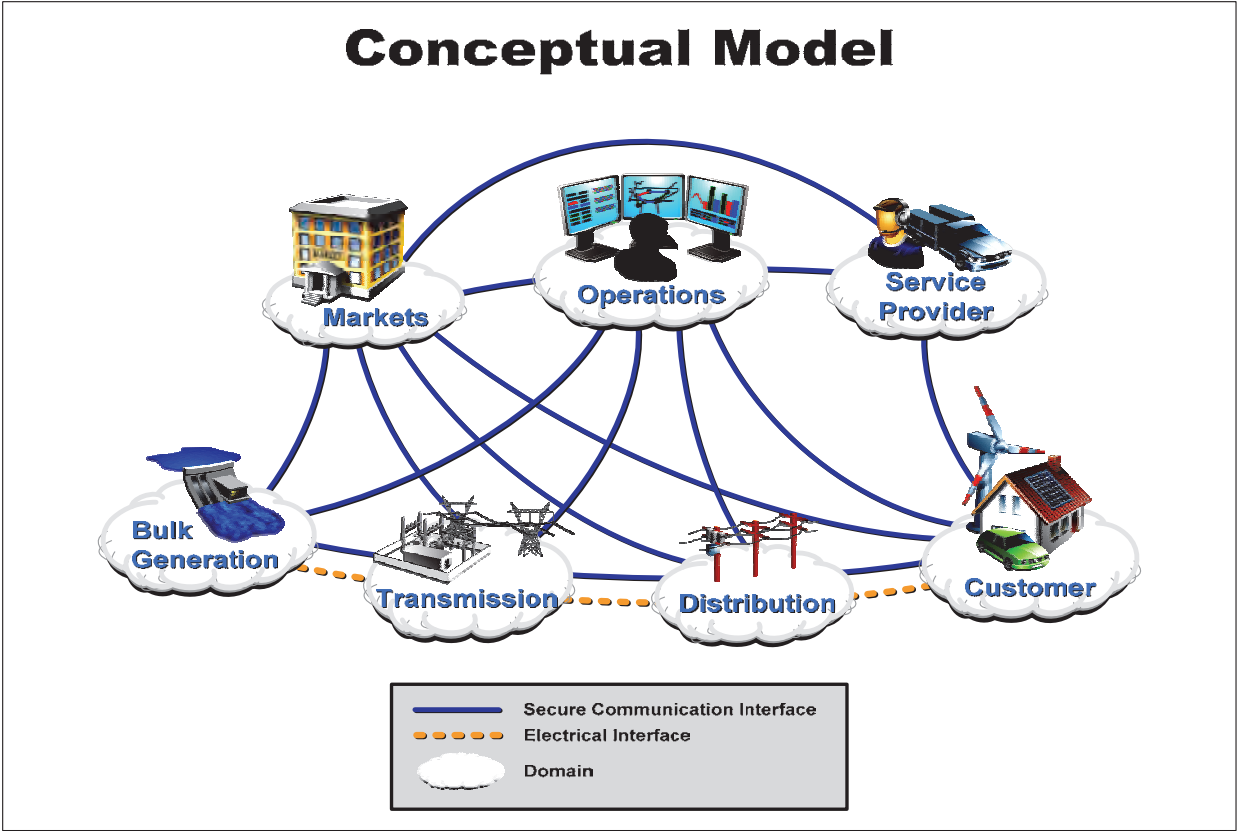


Fig. 1. Smart Grid Conceptual Model

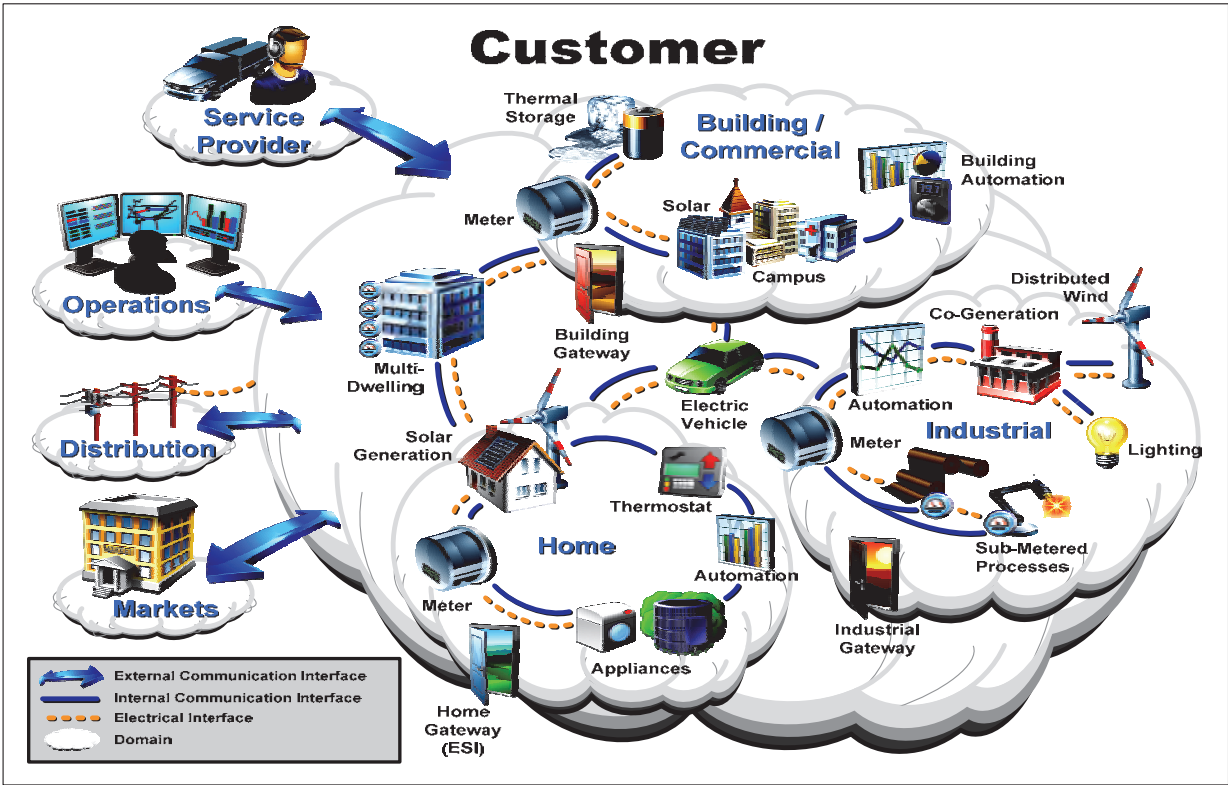


Fig. 2. Customer

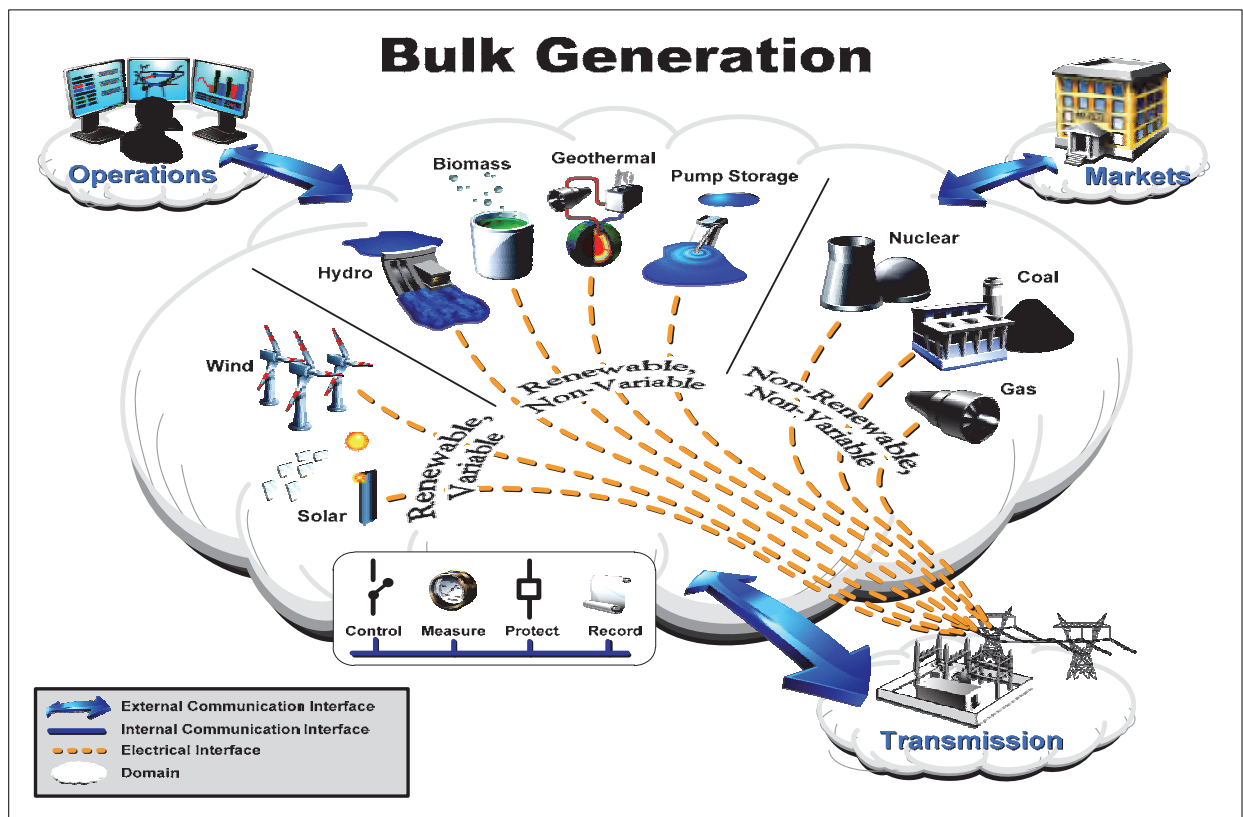


Fig. 3. Bulk Generation

providers will enable new capabilities which will be consumed by other domains. The operations domain integrates and balances network resources with the objective of achieving safe, secure and reliable real-time operations of the power system.

The bulk generation domain is categorized into: 1) non-renewable, non-variable, 2) renewable, non-variable and 3) renewable, variable generation. The first two categories represent traditional generation that can be dispatched when needed. The third category represents a new challenge for the grid.

Within the bulk generation domain, large quantities of renewable generation need to be integrated into the grid. The ideal generation would be in the form of renewable, non-variable. This would permit the generation source to be dispatched by the regional balancing authority. Renewable, variable generation such as wind and solar require fast-responding reserve generation such as spinning reserves or natural gas turbines to take over when the wind stops blowing or the sun becomes blocked by clouds. This requirement adds significant costs and impedes the growth of variable renewables, even if the occurrences are rare. Renewable generation on the grid currently amounts to 4% of the overall generation. The goal of increasing this to 30% will result in a grid that has significantly more variability than the current grid. Could a more cost effective and reliable approach include bringing customer energy curtailment resources into the feedback loop through the use of dispatchable high-performance demand response?

3. Smart Grid feedback loops

Bringing the customer further and further into the energy loop is an important facet of Smart Grid development that requires more analysis.

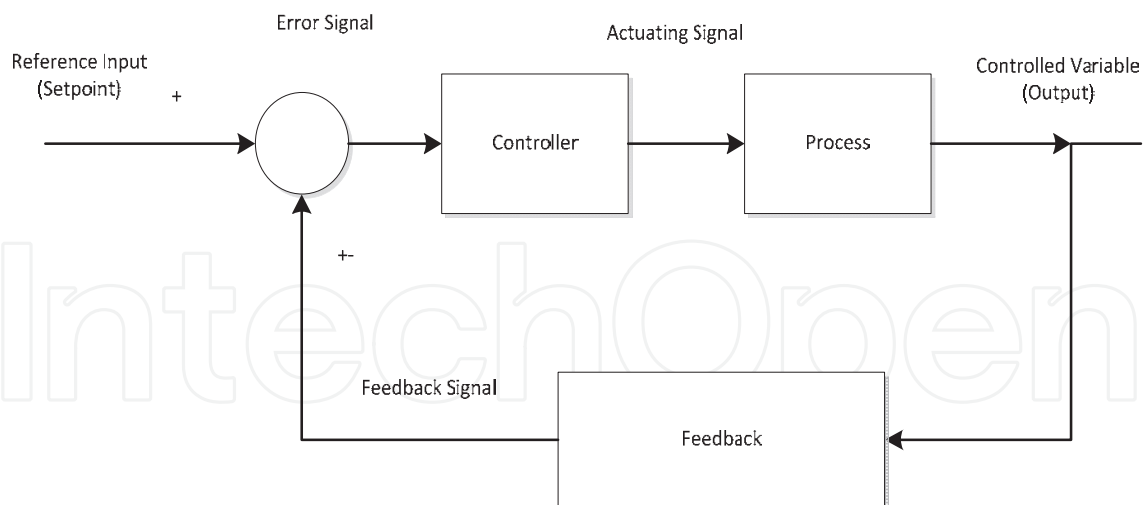


Fig. 4. Balancing Feedback Loop

Smart Grid is a system of systems tied together with large, wide-area feedback loops. These feedback loops constitute the basic behavioral operating unit of a system of systems. (Meadows, 2008) They can bring either stability or instability to the system. They can create growth or shrinkage of the system.

Feedback loops return an amplified portion of the output signal back around to the input where it either adds or subtracts from the input signal. This simple basic structure forms the foundation for automatic control theory which is widely applied within a number of domains including manufacturing automation, aircraft control and automotive systems.

If the feedback signal tends to subtract from, or offset, the input signal and decrease the output, it is a negative or balancing feedback loop. If the feedback signal adds to the input signal, it is a positive or reinforcing loop. The system and feedback loop have transfer functions, usually expressed in terms of Laplace transforms, which relate the output signal to the input signal. The behavior of the loop when any given input signal is applied can then be determined. The transfer function has solutions called poles and zeros under which it either drives the loop toward oscillation or becomes zero. Both conditions have negative impact if the loop is a balancing loop.

An example of a simple on/off balancing loop is the home thermostat. The desired balance point is the temperature setpoint. The feedback signal is the room temperature. When the room temperature reaches the setpoint temperature the heater is turned off until the temperature decreases below the setpoint. This digital loop inherently oscillates and relies upon the high capacity and slow response of the room and heating system to achieve acceptable results.

Reinforcing feedback loops amplify the output by building upon themselves resulting in exponential growth or collapse. The rate of growth is determined by the amount of feedback or gain.

An example of a simple reinforcing loop is compound interest where the interest earned on a financial account is fed back into the account resulting in the exponential growth of the account value over time.

A fundamental property of feedback loops is that they have a propensity to oscillate. This oscillation is caused by loop time-delays, or deadtime, that lead to the phase-shifting of feedback signals. If the resulting phase-shift is equal to 180 degrees, then a negative feedback signal turns into a positive feedback signal. This causes balancing loops to become

reinforcing loops and if the strength of the feedback is sufficient (i.e. product of loop gains ≥ 1.0), they become unstable and oscillate. Sufficient upfront system design is required so that this condition does not arise. (Shinskey, 1979)

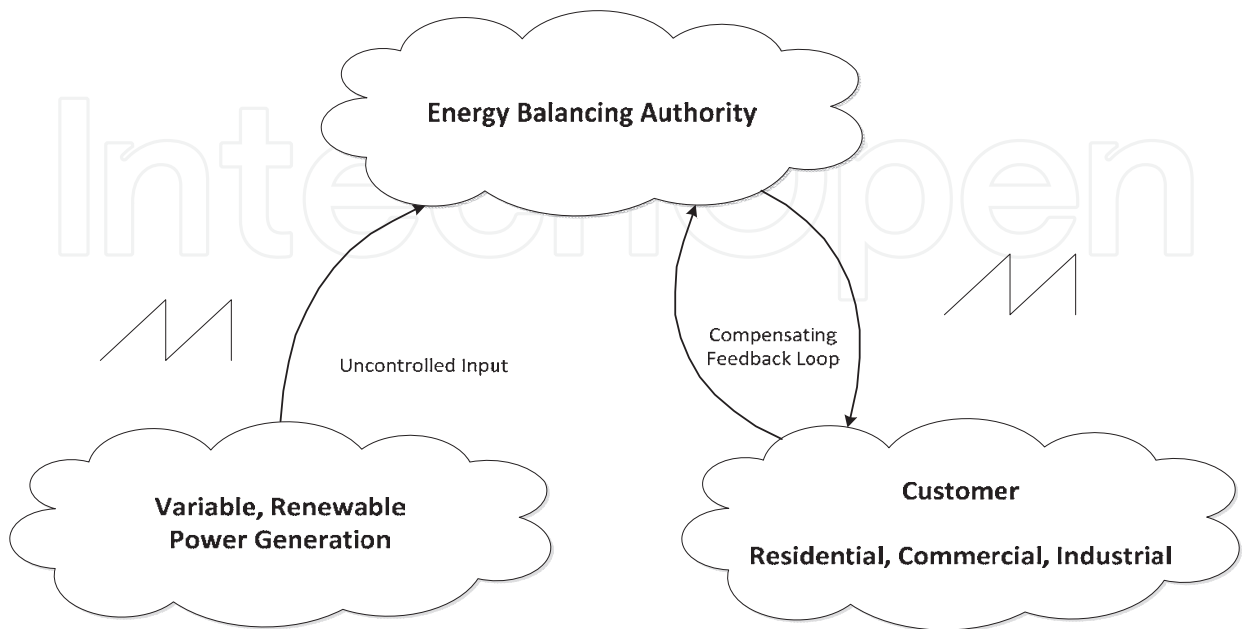


Fig. 5. Dynamic Power Feedback Loop

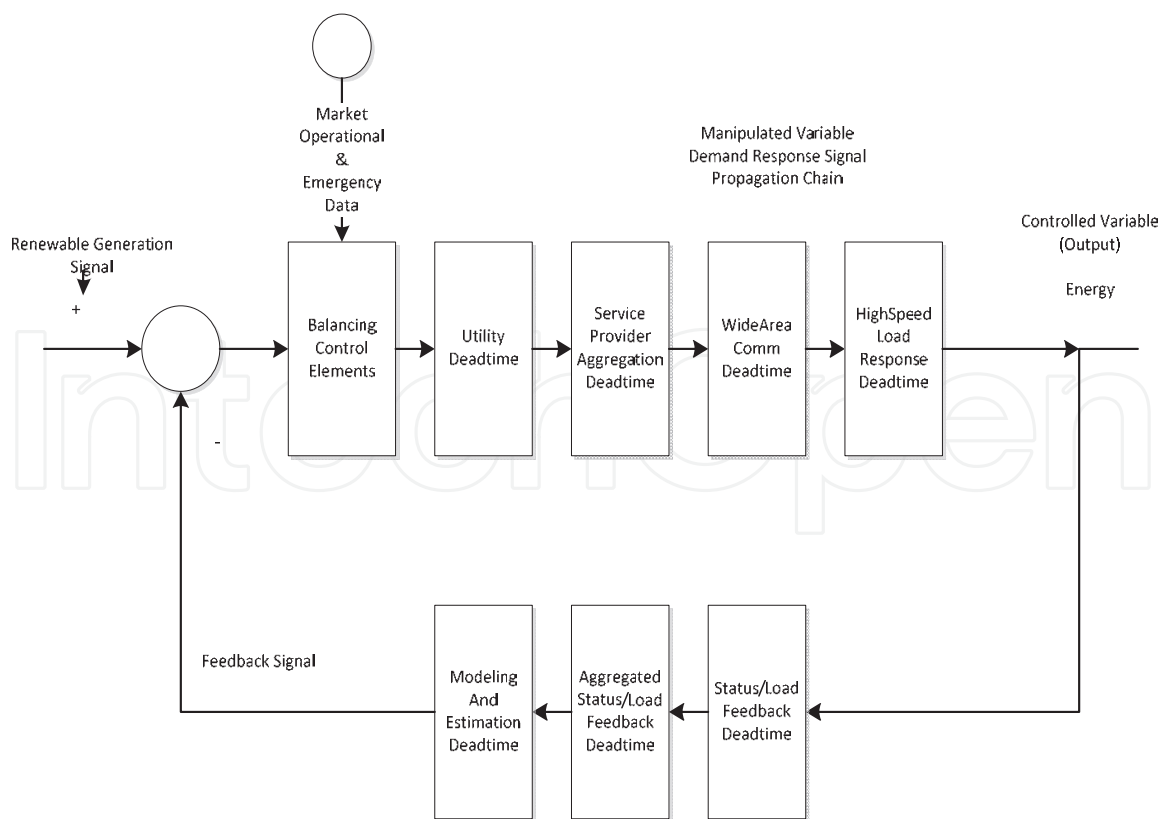
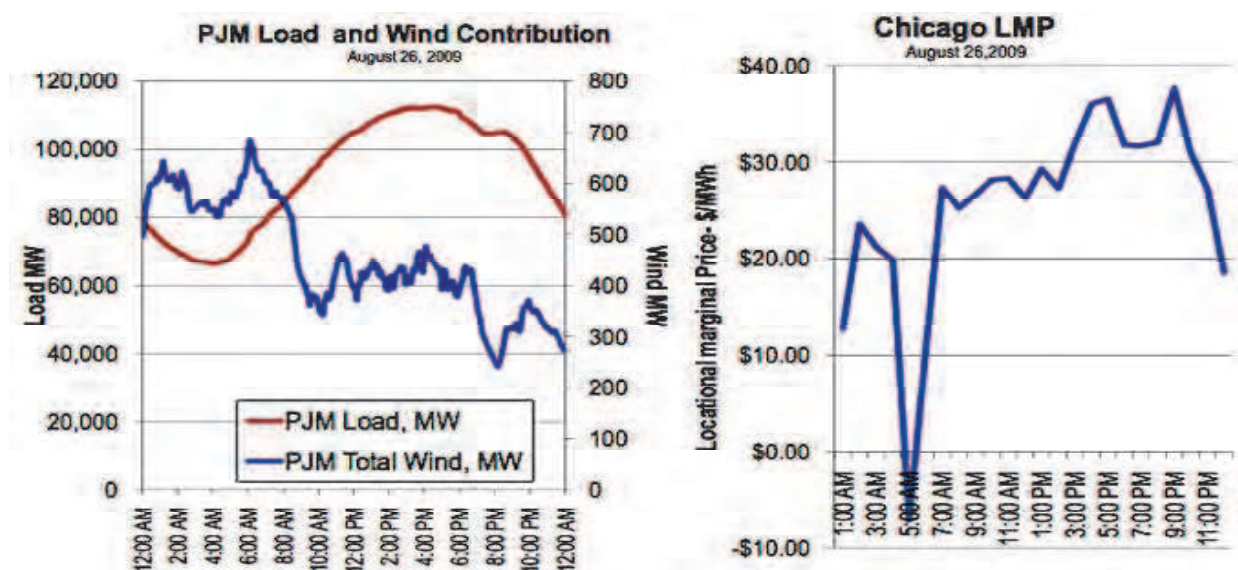


Fig. 6. Simplified Renewable Generation Demand Response Loop Diagram

Complex systems of systems are affected by large numbers of interacting feedback loops. Some of these loops have little effect on overall system behaviour while other loops can dominate system behaviour. In this context, an important and dominant smart grid feedback loop is the one that connects variable, renewable generation, such as wind and solar energy, with the power consumption of the customer. This loop is shown in Figure 5. The balancing authority has the responsibility to maintain the electrical grid in balance at all times with the power supply equal to the power demand. As power from wind and solar generation is fed onto the grid, the balancing authority only has the ability to dispatch a decrease in renewable generation by disconnecting it from the grid but not the ability to increase its power output. Compounding this issue is the power variability due to wind and solar fluctuations. This is in contrast to traditional grid operations which typically vary over a 24-hour period with reserve generation capacity being brought online or taken offline based on demand load. PJM studies have shown significant impact on the bulk electrical system due to wind variability with a corresponding impact on the LMP (locational marginal pricing) wholesale energy price. (See Figure 7)



Source: PJM

Fig. 7. Wind Variability

The balancing authority can compensate for this variability by dispatching fast-responding generation, adding sufficient power storage capacity and fast ramp-down of customer load. All of these options however have an associated cost and response time. (Hirst & Kirby, 2003) Fast-responding generation in the form of spinning reserves or natural gas turbines are effective but very costly. Bulk storage represents a very good solution in theory but economical grid-scale storage systems are still being developed. Reducing customer load through energy demand response represents a solution that has already been proven successful in its ability to provide the dispatchable curtailment of large quantities of power but its use as a high-speed compensator for renewable variability represents an area of growth and opportunity. (Kalisch, 2010)

The feedback system consisting of renewable generation, a balancing authority, utilities, service providers and customers can be described by a simplified renewable generation

demand response feedback loop diagram, Figure 6. This loop does not include fast-response generation or power storage elements.

The demand response loop is being driven by the uncontrolled renewable generation signal. If the renewable generation decreases, then the signal to the loop calls for a decrease in customer demand. The signal then propagates through several control and time-delay elements before aggregated customer power ramp down occurs. The feedback signal provides near real-time information including state and status data along with the actual power curtailment. Based on this information, the loop balances the curtailment with the generation. In order to remain stable and not oscillate, the loop needs to respond faster than the renewable generation driving signal.

This is very similar to industrial supervisory setpoint control. Supervisory control often utilizes a cascade loop consisting of a primary outer-loop which sends a setpoint signal to a secondary inner loop. The inner loop has faster response dynamics than the outer loop allowing it to track changes in the supervisory setpoint without becoming unstable and oscillating. Many considerations, such as loop windup, need to be taken into account due to the interactions between these two loops. (Skinskey, 1979)

The importance of inner loop response time means that the time-delays and latencies within a demand response loop need to be minimized as much as possible so that the overall loop response can be minimized. This includes both communication latencies and process delays. Applying this concept to demand response for renewable energy, the resulting loop dynamics determine how fast and effective the demand response loop will be in compensating for variations in renewable generation. The faster the loop response, the more effective demand response will be in mitigating real-time variance in renewable generation. One of the primary elements that contributes time-delays is customer load response.

4. Customer load response

Customer demand response can be characterized by the magnitude and speed of load response. This applies to both dynamic pricing and demand response event signalling. Four categories have been identified for classifying demand response performance. Each category, described below, will have different feedback loop dynamics and will affect the customer in different ways. Systems with large energy storage capacity are ideal for demand response applications in all categories listed.

Category 1: soft demand response

The response time required in soft demand response is often flexible and can vary from hours to days. Soft demand response events are targeted at the daily power consumption macro cycle which is driven by higher usage during the day followed by lower usage during the night. Energy curtailment can typically be planned and scheduled in advance.

Load response strategies include both load shedding as well as load shifting. Load shedding involves curtailing equipment that is not mission critical and load shifting is the rescheduling of energy-intensive operations to a different time period. This includes production lines and processing equipment.

Equipment typically curtailed includes:

1. External and internal lighting including parking lot lighting
2. External water fixtures
3. Air handlers

4. Anti-sweat heaters
5. Chiller controls and chilled water systems
6. Defrost elements
7. Elevators and escalators
8. HVAC (Heating, Ventilation and Air Conditioning) Systems
9. Irrigation pumps
10. Motors
11. Outside signage
12. Pool pumps and heaters
13. Refrigerator systems
14. Water heating systems

The load response times of these systems vary from seconds to hours. Longer response times can be accommodated through pre-ramp down control strategies while equipment with faster response times can be actuated directly.

Category 2: firm demand response

The response time required in firm demand response varies between five (5) minutes and ten (10) minutes. This aligns with ten-minute wholesale ancillary markets.

Firm demand response provides the grid balancing authority with the ability to balance a reduction in generation capacity with a compensating reduction in load. This category is appropriate for balancing variable renewable generation that has sufficient inertia, capacity or prediction.

Examples of equipment typically capable of firm demand curtailment include:

1. External and internal lighting including parking lot lighting
2. External water fixtures
3. Air handlers
4. Elevators and escalators
5. Irrigation pumps
6. Motors
7. Outside signage
8. Pool pumps

Category 3: near realtime demand response

Near realtime demand response requires response times of one (1) minute to five (5) minutes. These are appropriate for fast responding ancillary energy markets driven by significant quantities of variable renewable generation.

Only equipment capable of high speed ramp down can participate in near realtime demand response. Typical examples include:

1. External and internal lighting including parking lot lighting
2. External water fixtures
3. Air handlers
4. Irrigation pumps
5. Motors
6. Outside signage
7. Pool pumps

Category 4: realtime demand response

Realtime demand response require response times from one (1) second to one (1) minute. These applications include power frequency and load regulation as well as emergency

response to grid faults. Realtime response requires very high speed equipment shutdown capability as provided by motor-driven equipment or lighting.

In general, the ease with which a customer can react will decrease moving from category 1 to category 4. In order to achieve five (5) minute down to one (1) minute response, the decision making processes involved in load shedding, shifting or shaping must be automated and streamlined in order to provide a high degree of determinism and reliability. Demand response signals will contain both discrete and continuous information. Discrete information will often be in the form of dispatch triggers that initiate action. Continuous information will be in the form of value metrics such as dynamic pricing which will be used as input into decision-making algorithms.

5. Commercial and industrial dynamic power management strategies

The electrical energy consumed and produced within commercial and industrial (C&I) facilities represents a major percentage of the overall electrical energy consumed in the United States. The Department of Energy (DOE) estimates (US EIA, 2011) that 50% of the electrical energy produced in the United States is consumed within the commercial and industrial sectors. Residential homes consume an additional 22%. Commercial and industrial facilities have large power footprints distributed over a relatively small number of sites resulting in power densities that provide economies of scale and increase the potential impact these facilities can have on the bulk electric system.

This potential impact is offset by the primary business objective of commercial and industrial facilities to provide products and services for their customers. Electrical power is one of many resources necessary to produce these products and services. The level of interaction of any specific C&I customer with demand response signals can be directly related to the economic impact that electrical energy has on its operations coupled with the operational flexibility of rescheduling production. The more energy required producing products and services, the more effectively dynamic power management techniques can be applied.

Large commercial and industrial facilities consist of complex processes through which raw materials and other resources are combined and transformed into useful products. The ISA-SP95 standard consists of a four (4) layer model which describes how and where decisions are made concerning manufacturing processes. (ISA 95) (See Figure 8)

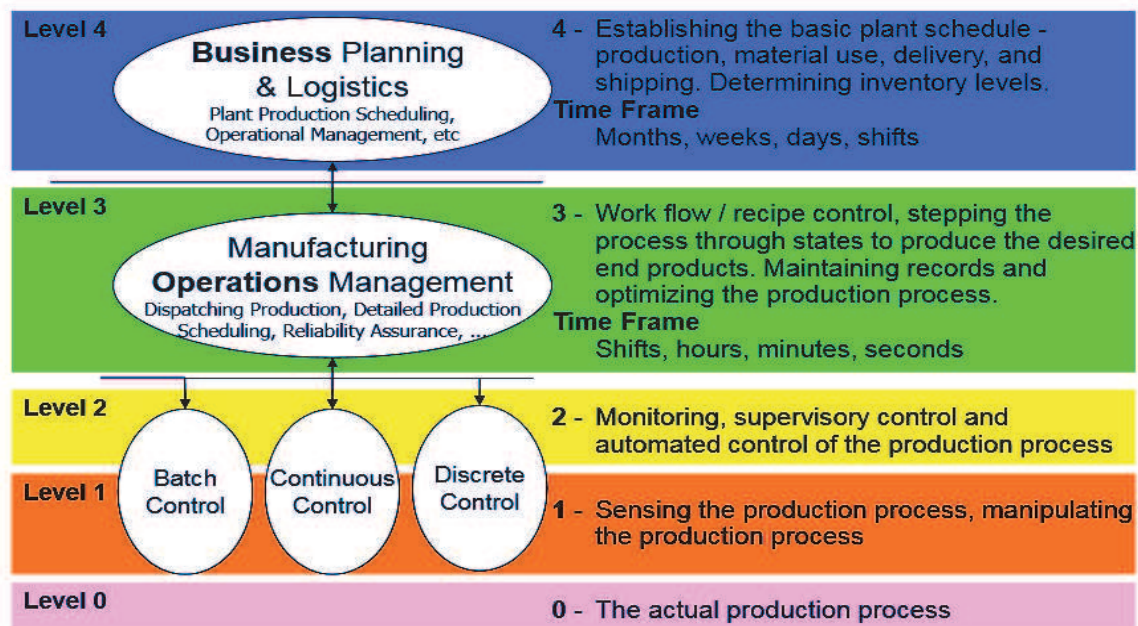
The four layers include:

- Level 4 – Business
- Level 3 – Operations
- Level 1 and 2 – Control

Dynamic power management decisions can occur within each of these layers. Decisions at Level 4 represent business decisions where the response to grid signals can be planned and optimized in context with the business as a whole. Decisions at Level 3 represent operational decisions where the response to grid signals is determined by supervisory systems in context with manufacturing operations. Decisions at Level 1 and 2 represent control decisions where the response is determined by control system logic running in programmable logic controllers and other automation devices.

Each level is characterized by both the amount of load reduction available coupled with the ramp rate of that load reduction. Decisions made at higher levels can typically provide more load reduction but require longer time intervals while decisions made at lower layers can provide faster response but provide less load reduction. The overall response of a facility will be determined by the contributions of all levels.

ISA 95 Levels – Distinct Sets of Activities



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Fig. 8. ISA 95 Levels¹

Demand response signals enable C&I customers to locally manage and optimize their energy production and usage, dynamically in real-time, as an integral participant in the electrical supply chain. These interactions permit customers to adapt to changing conditions in the electric system but they also require the use of advanced automation and applications in order to fully achieve the potential benefits.

An example of a typical interaction involves a manufacturer that bids demand response load reduction into a 5-min reserves ancillary market of the local balancing authority through a local service provider. These contingency reserves provide fast ramping of demand resources in the event of a generator or line trip. The manufacturer interfaces grid dispatch signals from the service provider directly to the industrial automation system in order to execute fast-ramp down of several large loads that can be interrupted without affecting the production line. The service provider receives the dispatch event and cascades the event to all participating industrial sites. In some cases, there will be fewer participants localized within a constrained region but in other cases, there will be large numbers of participants spread over a large region. Each site must receive the signal in a timely fashion to maximize its ability to reduce load in the short time window provided. The on-site dynamic power management system monitors the event and feeds back real-time event performance to the service provider. The service provider in turn summarizes and feeds back to the balancing authority concerning overall reserve capacity provided.

This is one of many scenarios and markets that will require C&I customers to respond rapidly and efficiently to demand response signals originating from the grid.

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6. Smart grid technology trends

Smart Grid enables two technologies that have a direct impact on the dynamic management of energy. These are; 1) microgrids and distributed energy generation and 2) transactive energy. Most C&I facilities are consumers of electrical energy but only a subset generate power on-site. Distributed generation permits more facilities to generate on-site energy and become self-contained microgrids (Galvin & Yeager 2008) connected to the electrical system. These microgrids will benefit both the electrical distribution system as well as the facility while helping to optimize the system-wide generation and consumption of energy.

Microgrids are self-contained, grid-connected energy systems that generate and consume on-site power. These systems can either import power from, or export to, the grid as well as having the capability to disconnect (or island) from the grid. The decision making process required to determine the best mode of operation requires taking into consideration both local operations as well as grid operations.

When external power cost is relatively high, a strategy based on exporting excess power generation and minimizing imported power would be the best course of action. If the cost of external power goes below the cost of self-generated power, then maximizing the power imported from the grid while decreasing on-site generation would be a suitable strategy. If an emergency or fault occurs on the external grid, the microgrid load can be curtailed or disconnected from the grid and reconnected when conditions permit.

The infrastructure needed to manage power supply and demand in context with the power grid enables the economically-viable expansion of on-site microgrid generation to include renewables and storage. These distributed energy resources (DER) are then presented as assets to the grid while being maintained and supported within the microgrid. Renewable generation includes not only solar and wind farms but also power harvested from process by-products or process energy stored as heat or pressure.

Today's centralized control of the power grid will evolve toward distributed control with more localized, autonomous decision making. These decision-making "software agents" will interact with other agents to optimize the energy utilization of connected devices and systems. These interactions, known as transactive energy, will be in the form of transactions with other systems which will be based on local economics and context.

Wholesale markets provide customers and service providers with the ability to bid large resources (typically greater than 1 MW) while retail markets will enable smaller energy transactions to occur as they become economically viable. These can be considered "micro transactions" and will occur between energy providers and consumers.

The microgrid is one form of autonomous system but as transactions involving the buying and selling of retail power evolve toward smaller and smaller entities, decision making will become more and more granular. Energy transactions could occur between components within microgrids, between microgrids, between microgrids and even smaller self-contained energy systems such as "nanogrid" homes and buildings.

Transactive energy does not change the requirement that the power grid must operate in a stable state of equilibrium with supply equal to demand. Autonomous market-driven behaviour creates system oscillations and instabilities through positive reinforcing feedback cycles. This behaviour can be very detrimental for grid-scale operations and must be managed proactively to avoid negative side effects.

As with variable renewable generation, an increase in the use of value-based economic or market-derived signals, such as dynamic pricing, to modulate energy consumption will

increase the dynamics of the power grid. These value-based signals need to be injected into the customer feedback loop so that acceptable stability is maintained. Techniques must be implemented that limit the operating range within which market activity is permitted.

These techniques need to not only limit the acceptable operating range but must also limit by rate-of-change and duration.

7. Conclusion

Dynamic power management is a key enabler for the integration of large quantities of renewable power generation onto the electrical grid. These renewable energy resources will significantly increase the variability of electrical power and impact the dynamics and stability of the power grid. Maintaining a reliable and stable grid will require that these dynamics be balanced in real-time.

Smart Grid enables customers to dynamically manage power usage based on electrical grid operating conditions and economics. Through systems integration, grid stability and reliability are enhanced while the customer benefits from lower costs and more reliable electrical power.

An important method for providing grid balancing is through the use of compensating negative feedback loops which leverage customer demand to offset variation in supply. These feedback loops will have an inherent tendency to oscillate if not designed and operated within acceptable boundary constraints relating to closed loop gain and phase shift caused by time delays and latencies.

These closed loop constraints subsequently bind the time requirements for customer load response. This increases the importance of deterministic response time when integrating customer demand response and dynamic power management strategies with real-time power grid operations.

Customer demand response is not limited to load reduction. Comprehensive dynamic power management strategies integrate on-site convertible process energy storage, distributed renewable generation and CHP (combined heat and power) co-generation into a portfolio of distributed energy resources (DER) with a range of response and load capability. Resources that provide fast-enough response can participate as active elements in the closed renewable generation demand response feedback loop.

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This book comprises of 13 chapters and is written by experts from industries, and academics from countries such as USA, Canada, Germany, India, Australia, Spain, Italy, Japan, Slovenia, Malaysia, Mexico, etc. This book covers many important aspects of energy management, forecasting, optimization methods and their applications in selected industrial, residential, generation system. This book also captures important aspects of smart grid and photovoltaic system. Some of the key features of books are as follows: Energy management methodology in industrial plant with a case study; Online energy system optimization modelling; Energy optimization case study; Energy demand analysis and forecast; Energy management in intelligent buildings; PV array energy yield case study of Slovenia; Optimal design of cooling water systems; Supercapacitor design methodology for transportation; Locomotive tractive energy resources management; Smart grid and dynamic power management.

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